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INDUCTIVE DETECTION OF FRACTURES IN GEOTHERMAL SYSTEMS - PETROPHYSICAL ASPECTS AND GEOPHYSICAL IMPLICATIONS

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ABSTRACT

A reliable electromagnetic (EM) means of detecting and delineating geothermal fracture systems would facilitate geothermal reservoir development. To this end, there have been rapid advances in our geophysical capability to gather extensive electromagnetic data sets and to generate elaborate numerical simulations mapping electrical conductivity distributions to electromagnetic field responses. However, the nonuniqueness of electromagnetic interpretations requires that formal interpretations of EM field data be conditioned by geological constraints. Indeed, the electrical conductivity expression of a fault is far from intuitive and must be based on geological investigations.

FLUID TRANSPORT IN FRACTURED RESERVOIRS: IMPETUS FOR INDUCTIVE LOGGING

Fractures influence the migration and accumulation of groundwater, geothermal and ore bearing fluids, and hydrocarbons. Estimating the permeability of individual fractures and fracture arrays is an important problem with application to a wide variety of reservoirs in diverse environments (Price, 1966; Stearns and Friedman, 1972; Bruhn et al., 1997; Brown and Bruhn, 1998). The importance of fracture permeability to fluid production and injection in commercial reservoirs is well documented and in many reservoirs fracture permeability dominates over intergranular permeability (Hunt, 1996; Tsang and Neretnieks, 1998). This is especially the case in fine-grained sedimentary reservoirs and in geothermal reservoirs.

Considerable effort has been expended in the past several decades to characterize natural fracture patterns by field mapping and analysis of drill core (e.g. Price, 1966; Stearn and Friedman, 1972; Kulander et al., 1979), in characterizing fluid transport properties of both discrete fractures and fracture networks (Long et al., 1982; Purak-Nolte et al., 1988; Brown, 1989; Oda et al., 1997; Brown and Bruhn, 1998; Tsang and Neretneiks, 1998), and obtaining better insitu measurements of fracturing and fluid flow using down-hole logging tools (e.g. - Barton et al., 1997). In spite of this effort, predicting the occurrence, geometry, and fluid transport properties of fractures in reservoirs remains a difficult task, which is hindered by our inability to measure fracture heterogeneity and anisotropy insitu, by the tendency for flow to become concentrated or 'channelized ' within only a fraction of the fracture network, and by the response of permeability to stress changes and mineral precipitation during fluid production.

Determining the geometry and fluid transport properties of fractures in the vicinity of a well bore is fundamental to understanding fluid production and well bore stability. Several existing logging tools provide useful, but limited information. Acoustic logs allow one to infer the presence of fractures, but provide little information on fracture geometry and transport properties. Bore hole televiewer and microscanner logs provide measurements of fracture orientation, and rough estimates of fracture filling and aperture, for those fractures that intersect the well bore. This latter information can be used to construct statistical models of fracture network geometry based on fracture orientation and frequency, but lack robustness because fracture size and connectivity must be modeled in an ad hoc fashion (Oda et al., 1997). Furthermore, recent work has demonstrated that the heterogeneity and anisotropy of fracturing and fluid transport properties are not the same in a number of cases. For example, Tsang and Neretnieks (1998) summarized evidence for flow channeling as a common phenomenon in heterogeneous fractured rocks and Barton et al. (1997) demonstrated that fluid production is concentrated along fractures most favorably oriented for Coulomb fractional (shear) failure rather than ubiquitously within a complex network. These and similar results from other regions are motivating development of new fracture permeability algorithms to account for the effects of stress on fracture closure (e.g. Bruhn et al., 1997; Brown and Bruhn, 1998), and also provide new impetus to develop logging methods that sample a volume of rock around the well bore in order to more directly characterize fluid conducting fractures. The purpose of this paper is to examine inductive means of characterizing fracture zones - in particular, emphasizing the definition of an electrical conductivity structure of such a zone.

CONDUCTIVITY MODELS FOR FRACTURED ROCK

The morphological complexity, which can be encountered in fracture zones, is illustrated in several figures. Figure 1a shows a cross section of a fault zone. Although the zone as a dimensional scale of meters, the individual fractures are much smaller, and form a network.

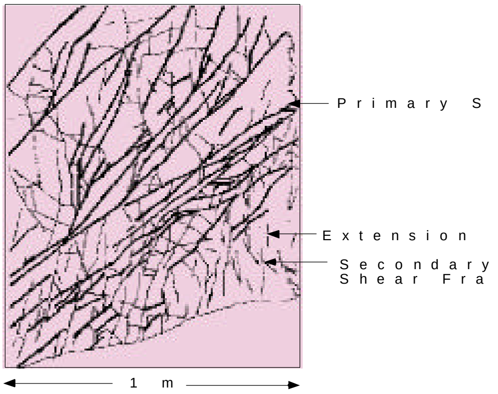

Figure 1a: Fault zone cross section.
Rather than "channels". Primary shear fractures have a given orientation, while secondary shears have a second orientation, and extension fractures have a third orientation. This pattern can be fractal and persist to different dimensional scales.

Figure 1b: Bedding surface fracture pattern.

Figure 1b illustrates a bedding surface fracture pattern taken from the Duchesne Fault. Again, the fracture patterns are complicated and highly anisotropic.

Fractures are also associated with folds. As Figure 2 demonstrates, these fractures again form networks with multiple orientations.

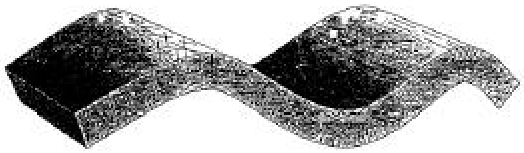

Figure 2

Geological observations of fracturing in outcrop and core can provide important constraints during the inversion of EM logging data by limiting the geometrical properties of the candidate fracture models. Important properties to constrain include the orientations, spacing, lengths, and connectivity of fractures in different rocks and tectonic settings. For example, fracture patterns vary markedly with location (Twiss and Moores, 1992). Fracturing in faults and fault zones differ significantly from that in intervening crustal blocks (Fig. 1a,b), and fracture patterns in folds change markedly with position between hinge and limbs (Fig. 2). Likewise, fracture spacing in sedimentary layers varies markedly as a function of both bedding thickness and lithology (Stearns, 1968; Twiss and Moores, 1992). Information on ambient stresses must also be considered because fracture permeability and storage parameters are a strong function of applied stress, which may change during production as fluid is either withdrawn or injected into the reservoir (Barton et al., 1997; Brown and Bruhn, 1998)

Figure 3 illustrates a generic fracture geometry, which can be assumed for feasibility studies. There is a fracture envelope, which has a dip and strike direction. Within the envelope, the fracture patterns form a network giving rise to an anisotropic pore fluid regime.

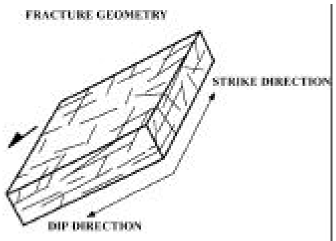

Figure 3

These figures suggest that the relationship between the electrical current density vector **J** and the electric field vector **E** for a fault zone should be

$$\mathbf{J} = \mathbf{s}\mathbf{E}, \qquad (1)$$

where **s** is a 3x3 conductivity tensor. In practice, the form of **s**_would be established from structural constraints on the fracture zone in question, established from field studies or as an a-priori assumption. The symmetries of the conductivity tensor are dependent on the symmetry properties of the fracture system, a dependence which can be determined using . group theory (Cracknell, 1968, Sec. 8.4)

Constraints on the form which the anisotropic **s** can attain, and its coupling with the magnetic susceptibility tensor **m**, are varied and are discussed by numerous authors, for example Weiglhofer (1993) and Kong (1986). Although the value of **m** can be significant for rocks containing significant amounts of magnetic minerals, it is usually safe to assume that **m** is diagonal, with all entries equal to μ_0.

The value of the entries of **s** depend on the geometry of the fractures in the network and their ability to conduct electricity. Both of these variables are dependent on the physico-chemical nature of the individual fractures. For example, Figure 4 gives a triangular diagram which illustrates the alteration of three different fault zones, each of which has "granitic" country rock. The mineral alteration should also change the microstructure, and hence the conductivity, of the fracture network. Changes in temperature will also affect the conductivity. For example, Sill et al. (1976) demonstrated that surface conduction associated with low temperature alteration in many geothermal environments could lead to large conductivities. The conductivity of the fracture fluid is also a factor.

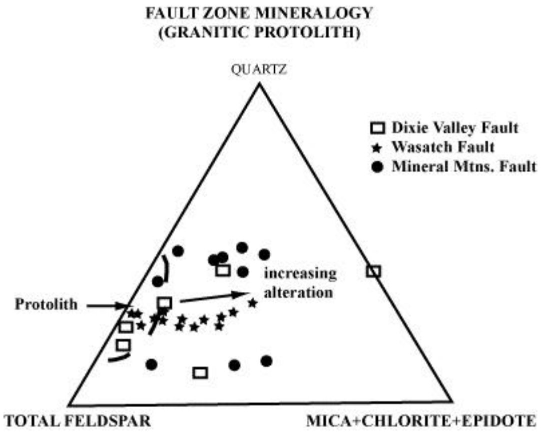

Figure 4

Quantifying the conductivity of a given fracture network is desirable because it is the foundation of any quantitative EM fracture detection and resolution. One approach has been suggested by Brown (1989), Brown and Bruhn (1998), Bruhn et al. (1997) and Oda et al. (1997). Figure 5 illustrates the conductivity tensor computed using this approach for a fracture system encountered in Dixie Valley.

NATURE OF THE EM RESPONSE OF FRACTURED ROCK

The characterization of the conductivities of fracture zones developed above can be used to develop a certain understanding of the possibilities and limitations of EM characterization of fault zones.

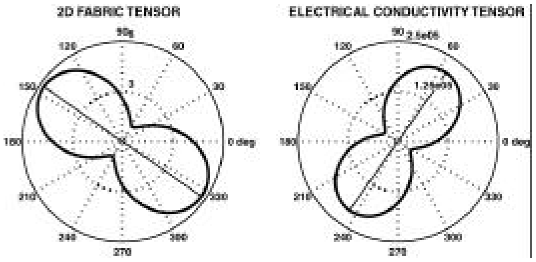

Figure 5: Conductivity Tensor for 2D-X sections of Dixie Valley fracture pattern. Multiply magnitudes by fluid conductivity to get true values.

First, it is important to understand that for diffusion regime measurements, the characteristics of the fault envelope itself are measured and estimation of the parameters of the envelope components, especially for complicated geometries, can be fraught with difficulties.

This point can be understood by considering a very simply model for a fault zone, which consists of a series of interbedded thin plates of two types - one representing fluid filled pore space and the other representing the unfractured rock matrix. Such a material would be uniaxially anisotropic, with transverse and longitudinal resistivities equal to

$$\rho_T = H_{\mu 1}\,\rho_{\mu 1} + H_{\mu 2}\,\rho_{\mu 2}, \qquad (2)$$

and

$$\rho_L = [\, H_{\mu 1}/\rho_{\mu 1} + H_{\mu 2}/\rho_{\mu 2}\,]^{-1}, \quad (3)$$

where ρ_T is the transverse resistivity and ρ_L is the longitudinal resistivity. $H_{\mu 1}$ and $H_{\mu 2}$ are the volume fractions of the pore space, denoted $\mu 1$ and matrix material, denoted $\mu 2$, such that $H_{\mu 1} + H_{\mu 2} = 1$, while $\rho_{\mu 1}$ and $\rho_{\mu 2}$ are the intrinsic resistivities of the component materials. This model can obviously be generalized to more than two components and to other than planar geometries, such as cylindrical or spherical fracture surfaces. Although this model is exceedingly crude, it may serve to suggest the interpretational non-uniqueness which may be encountered in analyzing a fracture response. For the diffusion regime and typical fracture zone dimensions, all that can be determined is ρ_T and ρ_L . The resistivities and the volume fractions of the components, in the absence of additional independent information, will remain unresolved.

Difficulties will be compounded for more elaborate mixing laws.

Additional independent information is required to alleviate these difficulties. For example, if a dielectric response of a fracture zone is also known, as might be the case if a MWD tool is run in the borehole, then rigorous bounds on the volume fraction of the fluid component can be found which are valid for any anisotropic geometry (Cherkaeva and Tripp, 1996c).

The geometry of the source fields can restrict resolution of the conductivity tensor.
To understand this point, consider Figure 6. This figure assumes that a fracture zone is a perturbation on a whole space. In this case, a uniaxial magnetic dipole source orientated in the z direction will have an electrical current distribution, which is azimuthal. Hence it will sample $\Delta\sigma_\phi$, but has no component in the z or the ρ directions. In this case, $\Delta\sigma_z$ and $\Delta\sigma_\rho$ are unresolved. The composition of two sources has no component in the r direction and hence $\Delta\sigma_r$ is unresolved. Only when there are three sources can one hope to resolve a general conductivity tensor.

There has been recent interest in developing induction tools for delineating fractures in geothermal systems (Sato et al., 1996; Wilt et al., 1997). Simultaneously, there has been growing interest in running and interpreting induction logs in strongly deviated boreholes and in the presence of anisotropic formations and anisotropic formations. (Klein, 1996; Klein et al., 1997). Consideration of Figure 6 demonstrates that for both applications, full resolution of the formation anisotropies requires the use of an induction tool with a triaxial source and a three component receiver. Some references on the feasibility of such a tool include Moran and Gianzero (1979), Howard (1981), deCarvalho and Verma (1994), Nekut (1994), and Jarrard and Tripp (1999). Cherkaeva and Tripp (1999) discuss means of focussing triaxial sources to optimize resolution for any conductivity perturbation.

It is possible to develop apparent resistivity expressions for the response of anisotropic material (Moran and Gianzero,1979). These author's show that bed boundaries and boreholes can have a significant impact on the accuracy of the formation conductivity estimate.

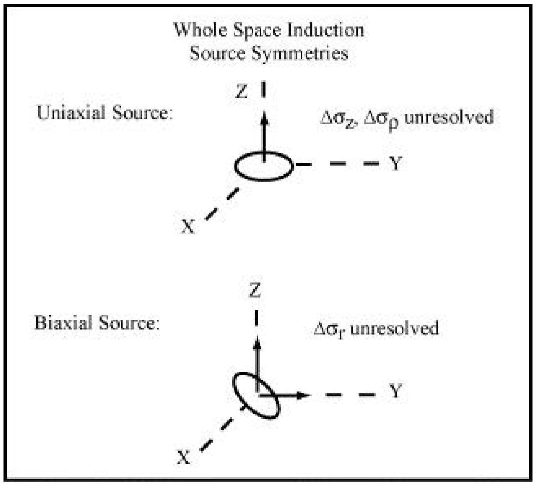

Figure 6

SYSTEMATIC INTEGRATION OF GEOLOGICAL KNOWLEDGE DURING INVERSION OF LOGGING DATA

A major conclusion of this study is that while a technological basis for inductive fracture detection exists, there is a serious need to incorporate independent geological and geophysical information to maximize resolution of fracture zone parameters. The manner and degree to which geological knowledge is incorporated into modeling algorithms will of necessity depend on the type of available data, and limitations of various knowledge system algorithms. The geologic knowledge system may be implemented prior to inversion, in which case basic geometrical elements of the starting model are constrained to lie within a specified parameter space, or implemented following inversion to evaluate model fitness or 'uncertainty'. Neural networks are appealing for those cases where sufficient case histories or 'training sets' are available for tectonic and geologic settings similar to that under study. However, implementing a neural network with back propagation learning rules requires development of a large training set, which may be difficult to develop given the variability in the type and quality of data used in published geologic case histories (Caudhill and Butler, 1993). Rule based expert systems provide an alternative to neural network algorithms, and these may be the simplest to implement using available published case history data sets. Uncertainty may be included in the rule based system using logic tree methods with ' expert elicitation by practicing geologists', in a manner similar to that used for probabilistic evaluations of seismic and other natural hazards (Coppersmith and Youngs, 1986; Kramer, 1996).

It is appealing to speculate that cooperative interpretation of multiple data sets could assume the form of a cooperative game, in which the objective function is vector valued. In this case, the optimization would be to identify a multiplicity of solutions. It might also be productive to identify such a system with an ecosystem which is "evolving" toward fitness (See, for example, Casti and Karlqvist, 1995)

CONCLUSIONS

Electrical detection of fault and fracture zones is optimized by careful considerations of auxiliary geological information.

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